Compact and high-quality gamma-ray source applied to 10 μm-range resolution radiography

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Gamma-ray beams with optimal and tuneable size, temperature, and dose are of great interest for a large variety of applications. These photons can be produced by the conversion of energetic electrons through the bremsstrahlung process in a dense material. This work presents the experimental demonstration of 30 μm resolution radiography of dense objects using an optimized gamma-ray source, produced with a high-quality electron beam delivered by a compact laser-plasma accelerator. © *2011 American Institute of Physics*. [doi:10.1063/1.3604013]

Gamma-ray sources, widely used in medical, industrial, and scientific research activities, are currently produced by using radioactive isotopes, the bremsstrahlung process in a dense material and the Compton scattering of an intense laser onto relativistic electrons. Among these, bremsstrahlung radiation is today the only process that can be used for single-shot measurements or applications with high luminosity, high energy, and very small source size.

The bremsstrahlung radiation method is currently applied using "conventional" particle accelerators where high-energy electron beams are converted into gamma-ray beams as they pass through a dense target. Production of electron beams also with high energies and low emittance is now possible with compact facilities, the laser-plasma accelerators. This recent generation of accelerators is based on the use of an ionised medium to accelerate charged particles. The resulting accelerating electric field is then not limited by material breakdown[1] and the corresponding gradient can reach very high values exceeding several hundreds of GV/m.[2]

Quasi-monoenergetic electron bunches accelerated by plasma-waves to the 100 MeV level were produced by several groups in 2004.[3–5] Stable electron beams with tunable energy, charge, and energy spread were recently achieved using two colliding laser beam scheme.[6,7] Electron energies of more than 1 GeV were also reached in recent experiments by using capillary plasma discharges[8] and gas jets[9–11] with relatively long plasma lengths ranging from one to a few centimetres.

Energetic electron beams from laser-plasma accelerators were recently used to demonstrate the production of high-dose[12,13] and small-size[14] bremsstrahlung ray sources. This size was about 400 μm. Comparable gamma ray source dimensions (350 μm) have been also demonstrated using the interaction of an intense laser pulse with a thin foil target.[15]

Following the results performed with laser-plasma accelerators, we present in this article the experimental demonstration of an improved and optimized gamma-ray beam with even higher quality. This source, ten times smaller, was used in our experiment to perform radiographic studies of complex and dense objects with a resolution of a few tens of micrometers.

The experiment was performed at Laboratoire d'Optique Appliquée using the compact Ti:sapphire laser in "Salle Jaune."

The experimental set-up is shown in Fig. 1. The creation and the acceleration of primary electron beams are obtained by the interaction between an intense laser beam with a supersonic helium gas jet, generated by a 2 mm diameter nozzle.[16] The laser system, operating at a central wavelength of 0.8 μm, delivers 1 J at a repetition rate of 10 Hz. After compression, the laser pulse duration is about 30 fs which corresponds to about 30 TW peak power.

The 60 mm diameter laser beam is focused by a 1 m focal length spherical mirror to a 17×22 μm focal spot at full width half maximum (FWHM), giving a peak intensity of $I \approx 3.6 \times 10^{18}$ W/cm^2.

The gas density was adjusted so that the laser pulse duration would match the plasma wave period, allowing efficient plasma wave excitation. At a plasma density around

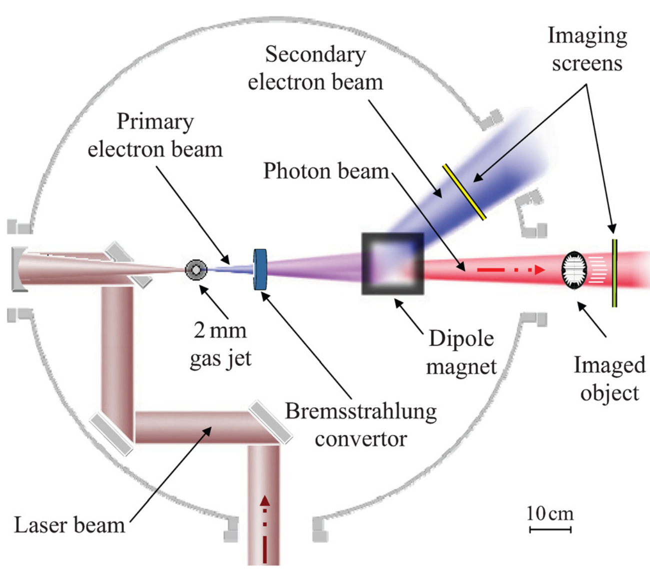

FIG. 1. (Color online) Lay-out of the experimental setup.

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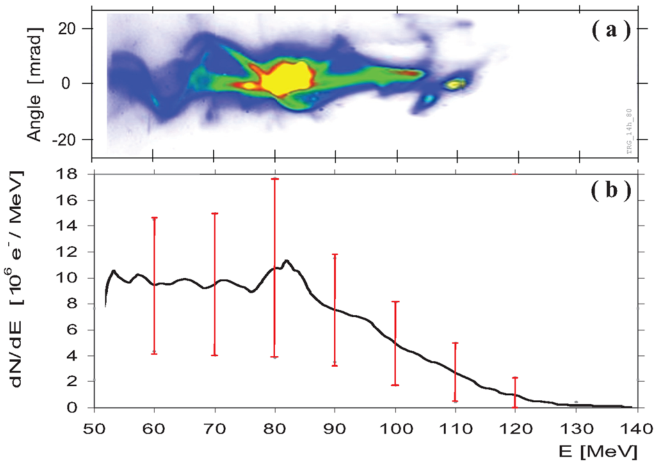

FIG. 2. (Color online) (a) Typical measurement of the electron spectrum and (b) the deconvoluted and average spectrum of twenty consecutive electron bunches. Error bars represent the (80%) rms charge fluctuations.

10^{19} cm^{-3}, electrons were "self-injected" and accelerated with quasi-monoenergetic distributions.

The electron beam spectra were recorded with an energy spectrometer consisting of a bending dipole magnet (1 T; 10×10 cm) and a phosphor screen (Kodak Lanex film). The beam charge and energy distribution were obtained using corresponding absolute calibration information[17] and measured with relatively small energy resolution (2% at 100 MeV and for a FWHM 5 mrad beam divergence).

The resulting electron beams had rather broad energy spectra containing a peak at around 80 MeV. The average charge, integrated between 50 and 130 MeV, was about 70 pC (cf., Fig. 2). The average electron beam divergence (including the whole energy spectrum between 50 and 130 MeV) was 3 mrad (FWHM).

A gamma-ray beam was produced by the electron bunch through bremsstrahlung inside a tantalum target with optimized geometry.[18] This target of 1 mm thickness was placed at 5 mm from the gas jet. The bending dipole magnet served to remove the secondary electrons leaving the conversion target.

The resulting photon beam spatial distributions were measured with 25 μm resolution by using a photostimulable phosphor screen (Fujifilm imaging plate). This detector was also highly sensitive to the signal produced by secondary electrons and low energy photons. In order to enhance the signal-to-noise ratio for the gamma-ray measurements, we added an optimized thin plate of 920 μm-thick copper, right before the detector. This plate allows converting the high energy gamma-rays into electrons and low energy photons, which increases the signal recorded on the Fujifilm detector.

The spatial resolution in object radiography is mostly limited by the size of the radiation source. The source size is expected to be very small in this experiment: The small initial size and divergence of the primary electron beam lead to an expected radiation size at the converter target of only a few tens of micrometers.

In the case of a monoenergetic photon beam, the source size is generally defined as the minimum root-mean-square (RMS) diameter of the propagating ray flux.[19] In this experiment, the minimum diameter is located inside and close to the output plane of the convertor.[18]

We measured the gamma-ray source size with the knife-edge technique, by imaging the sharp edge of a 1 cm thick steel plate. This edge was aligned on the laser axis and placed at 20 cm from the tantalum convertor in order to perform an image with a magnification of a factor 7 on the Fujifilm screen. This screen was positioned at 1.6 m downstream of the convertor.

Figure 3(a) illustrates a radiograph of the steel piece acquired with the resolution of 25 μm per pixel. The shadow of the corresponding edge can be seen in this image in the vertical direction. The profile of the measured photon density was computed along the perpendicular direction xx' and averaged over 3 lines of pixels (cf., Fig. 3(b)). The width of the profile gradient, Δs, at the edge of this steel plate is used to estimate the gamma-ray source size (cf., Fig. 3(c)). By taking into consideration, the magnification of a factor 7 on the detector, the deduced FWHM gamma-ray source size is equal to 30 μm $\pm$ 10 μm.

This source size is the smallest size demonstrated and measured for gamma-ray beams produced from a laser-plasma accelerator. The measurement is consistent with numerical results[18] computed for the same conditions of electron beam acceleration and the optimized geometry of the tantalum convertor with 1 mm thickness. Complementary simulations, using the same code and the Monte Carlo simulation tool GEANT4,[20] give gamma-ray source sizes between 40 and 80 μm for electron beam energies and divergences varying in the range of 70 to 130 MeV and 2 to 4 mrad, respectively.

The same simulations described above give a gamma-ray beam temperature of about 40 MeV, extracted from a Maxwellian fit of the energy spectrum. The resulting dose in air is equal to 0.25 Gy at 60 cm from the tantalum convertor, on the laser axis and for the case of a total electron beam charge of 100 pC.

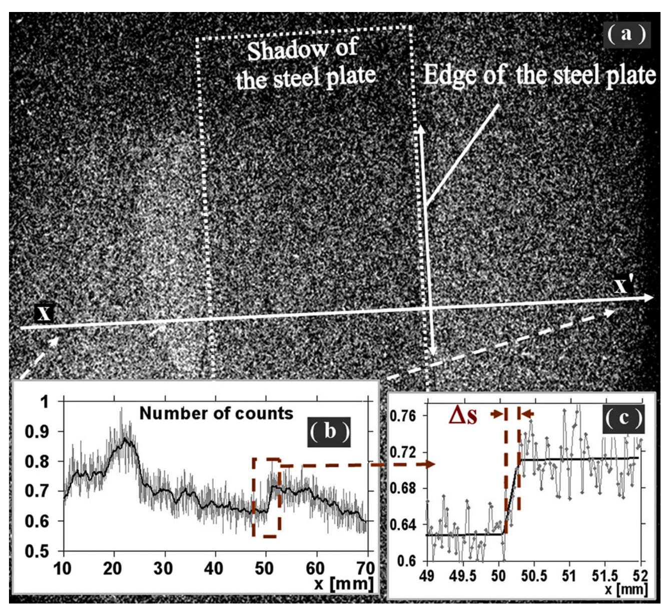

FIG. 3. (Color online) (a) Radiography of a steel piece for the photon spot size measurement. (b) The plot profile averaged over 3 lines of pixels, and (c) the corresponding magnified region around the edge of the steel piece.

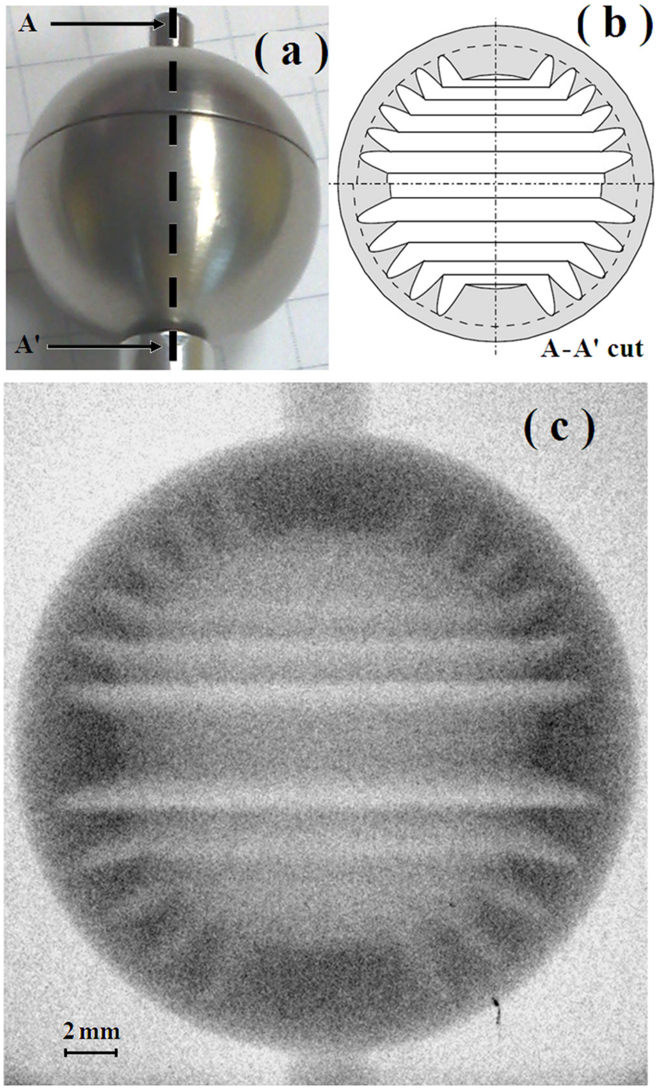

FIG. 4. (Color online) (a) Photo of the 20 mm diameter tungsten object, (b) a schematic A-A′ cut, and (c) the resulting radiograph with the optimized gamma-ray source.

The demonstrated spatial and spectral qualities of our gamma-ray source satisfy totally the necessary conditions for radiography of dense objects with very high resolution.

We have used the optimised gamma-ray source to radiograph a complex and dense tungsten object. This object is spherical, hollow, and etched on the inner part with sinusoidal structures with cylindrical symmetry (cf., Figs. 4(a) and 4(b)).

The spherical object with 20 mm diameter was placed on the laser axis, at 60 cm from the convertor and imaged on the imaging plate phosphor screen with a magnification of a factor 3. The resulting experimental image is shown on Fig. 4(c). The clear details of the inner sinusoidal lobes confirm the 30 μm-level resolution and validate the possibility of dense object radiography with the demonstrated gamma-ray source.

In summary, experimental results from a high-quality gamma-ray source were detailed in this article. This source was achieved using a compact laser-plasma accelerator. The gamma-ray source size was measured and reveals a value in the range of 30 μm. Such excellent resolution was obtained by using the optimum parameters (geometry and thickness of the convertor) resulting from previous numerical studies.[18]

The presented gamma-ray sources, with such high temperature, dose, and 10 μm-range size, are beneficial for fast and ultra-precise radiographies for example in automotive and aeronautics industries. These sources have the capability to identify sub-millimetric manufacturing defects, such as cracks, incomplete welds and other flaws that develop during service.

These gamma-ray sources are also an alternative for line radiations such as Kα line radiations produced when intense laser pulses irradiated a solid target. Such radiations are emitted in all directions and require a large amount of energy (in the 100 J level) to be useful for the case of imploding capsule radiograph. The source characteristics presented in this paper show that this required level of laser energy could be significantly reduced by keeping the same imaging quality. In addition, according to numerical simulations, the duration of the studied gamma-ray pulse is expected to be in the sub-picosecond range. This duration makes this source also of interest for the dynamical studies of imploding pellets in inertial confinement fusion experiments (studies of implosion stability, hydrodynamics instabilities, etc…).

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